Workshop summary report

Heavy Ions and New Physics

indico.cern.ch/e/Heavy-Ions-and-New-Physics

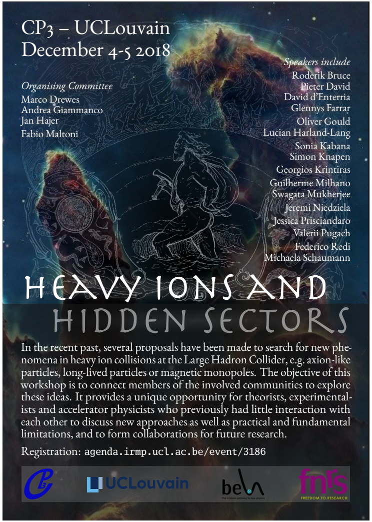
Jan Hajer

Universität Basel

Energy Frontier Workshop — Restart

Introduction

2018 workshop



Goals

Exploration of New Physics searches in heavy ion collisions

First workshop resulted in

contribution to 'European Strategy for Particle Physics' (ESPP)

New physics searches with heavy-ion collisions at the CERN Large Hadron Collider

Roderik Bruce[1], David d'Enterria[2,18], Albert de Roeck[2], Marco Drewes[3], Glennys R Farrar[4], Andrea Giammanco[3], Oliver Gould[5], Jan Hajer[3], Lucian Harland-Lang[6], Jan Heisig[3], John M Jowett[1], Sonia Kabana[7,16], Georgios K Krintiras[3,17], Michael Korsmeier[8,9,10], Michele Lucente[3], Guilherme Milhano[11,12], Swagata Mukherjee[13], Jeremi Niedziela[2], Vitalii A Okorokov[14], Arttu Rajantie[15] and Michaela Schaumann[1]

J. Phys. G 47 (2020) 6, 060501
e-print: 1812.07688 [hep-ph]

In the process of formulating a

contribution to Snowmass 2021

2021 workshop

Magnetic monopoles

Magnetic field in 5.02 TeV PbPb

$$|B| \simeq 4 \cdot 10^{16}\,\mathrm{T} \simeq 7\,\mathrm{GeV}^2$$

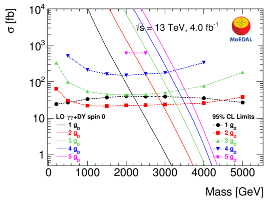
Magnetic charges

$$\nabla \cdot E = \rho_E \;,\; \nabla \times E = -\partial_t B - j_M$$
$$\nabla \cdot B = \rho_M \;,\; \nabla \times B = -\partial_t E - j_E$$

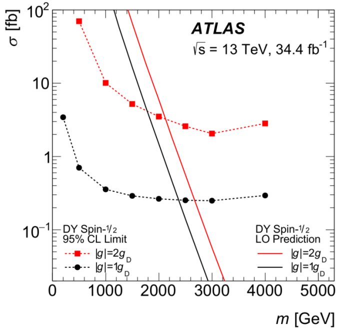
Dirac quantisation

$g \in g_D \mathbb{Z}$ with $g_D = 2\pi / e_0$

MoEDAL 2019



ATLAS 2019



Drell-Yan crosssection is wrong

$e \to g = 2\pi / e$ Duality

Because $g_D \approx 20.7 \gg 1$

Process is non-perturbative

Instanton tunneling action

$$\Gamma \propto e^{-S_{\mathrm{inst}}}$$

Monopole Schwinger production

$$\Gamma = \frac{g^2 |B|^2}{8\pi^3} \exp\left(\frac{g^2}{4} - \frac{\pi m^2}{g|B|}\right)$$

Needs strong magnetic field

Time dependence

enhanced production for rapid pulses

Spatial inhomogeneity

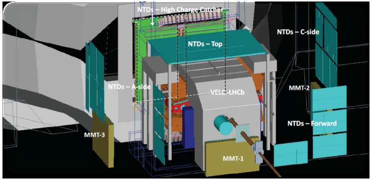
Effect not known

Solitonic monopole size

Enhances production

Magnetic monopoles in MoEDAL

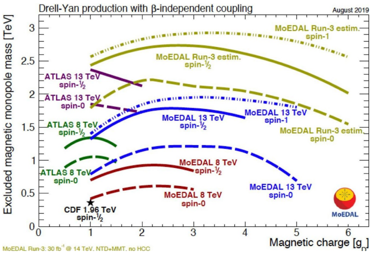
MoEDAL close to LHCb



Physics potential

- Magnetic monopoles
- Multiply charged particles
- Long-lived particles
- Mini charged particles
- *Q*-balls
- Strangelets
- Highly ionizing particles

Magnetic monopoles in *pp* 2019



Leading limits

$1.5\ \mathrm{TeV} < m < 3.75\ \mathrm{TeV}$

$2g_D < g < 5g_D$

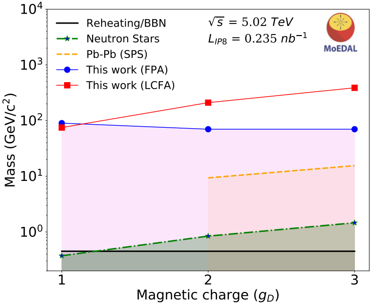
Only photon fusion and Drell-Yan

No non-perturbative effects

Magnetic monopoles in PbPb

New result: 2106.11933

Includes Schwinger production



Exclusion of masses up to 75 GeV

New Physics @ CMS

Magnetic monopoles

under investigation

Signature considerations

Non-helicoidal trajectory
Heavily ionising
Specific shower shape
If monopolium: decay to $\gamma\gamma$

Naive estimate for PbPb

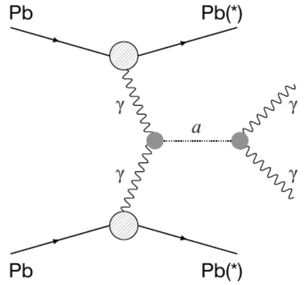
using Superchic3
only large clusters in tracker
no systematic uncertainties
$M \sim 400\,\mathrm{GeV}$ @ $95\,\%$ CL

Axion like particles (ALPs)

light pseudoscalar

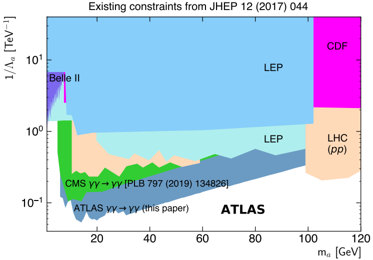
Often studied via $\gamma\gamma$ interaction

Ultra peripheral HI collisions



Best ALPs limits

$5\,\mathrm{GeV} < m < 6\,\mathrm{GeV}$



Cuts

$E_T > 2\,\mathrm{GeV}$
$|\eta| < 2.4$
$m_{\gamma\gamma} > 5\,\mathrm{GeV}$
$p_T < 1\,\mathrm{GeV}$
$A_\phi = |1 - \Delta\phi/\pi| < 0.01$

ALPs @ ATLAS

Search strategy

exactly two photons with
$E_T > 2.5$ GeV and $|\eta| < 2.37$

invariant mass $m_{\gamma\gamma} > 5$ GeV

Veto

no tracks with $p_T > 100$ MeV

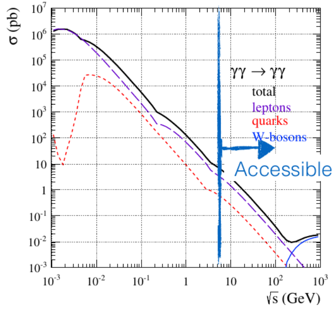
no pixel tracks with
$p_T > 50$ MeV and $|\eta_{t\gamma}| < 0.5$

Back-to-back topology

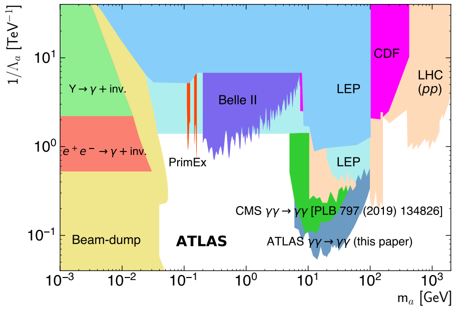
$p_T(\gamma\gamma) < 2$ GeV
reduced acoplanarity < 0.01

Partially exploits low trigger

Cross section steeply falling



Exclusion with $2.2\,\mathrm{nb}^{-1}$ 2021



ALPs @ LHCb

Study used

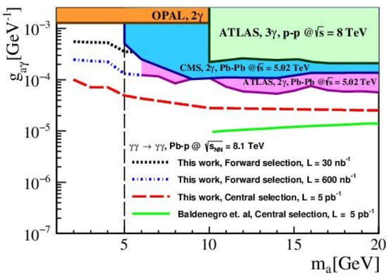
- Superchic3
- FPMC (modified for PbPb)

Acceptances included

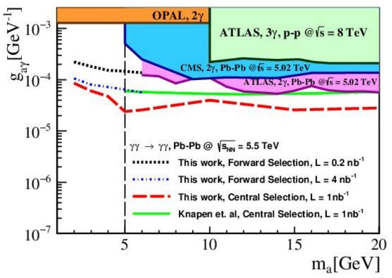
Main backgrounds

- light-by-light scattering
- di-electron with mis-identification

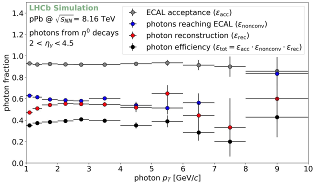
*p*Pb



PbPb



Photon reconstruction in *p*Pb



Expected to surpass current limits

for masses below 5 GeV

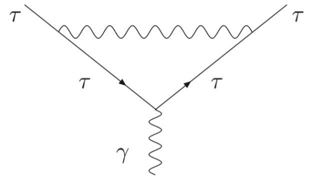
Light ALPs also accessible @ ALICE

Potential New Physics search without competition by CMS or ATLAS

τ-lepton $g-2$

anomalous magnetic moment

$a_\tau = (g_\tau - 2)/2$

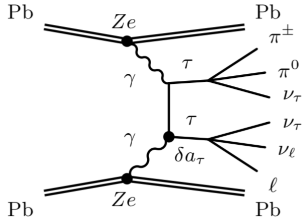


Constraint from DELPHI

$-0.052 < a_\tau < 0.013$

poorly constrained due to short lifetime

Measure in HI

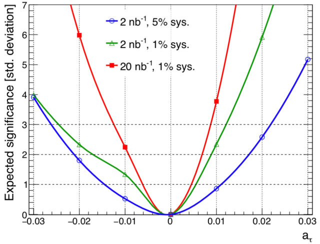


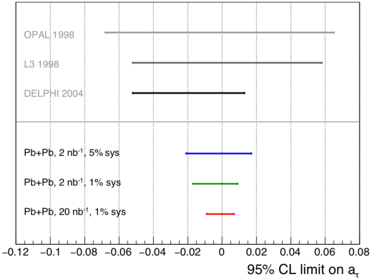
Differential distribution

Cancel uncertainties using

ratio to ee, $\mu\mu$ processes

Expected improvement





Sexaquarks

$S = uuddss$

spin, colour, and flavour singlet

$$m_S \approx 2m_p \qquad B = -2$$
$$Q = 0 \qquad S = -2$$

no pion interactions

Tightly bound and compact

$r_S \approx 0.2\,\mathrm{fm}$

Dark matter candidate

Quasi stable with $\Omega_{\mathrm{DM}}/\Omega_b \approx 5$ without free parameters

So far not excluded

Despite searches for the H-dibaryon with same quark content

Because search relies on

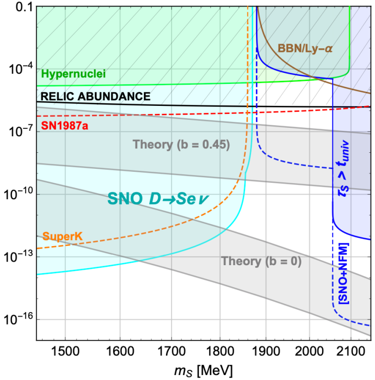
- unstable particle
- heavy particle ($> 2\,\mathrm{GeV}$)
- interaction with Λ

However

S is similar to neutron

Exclusion bounds on $S \to \Lambda\Lambda$

effective Yukawa coupling

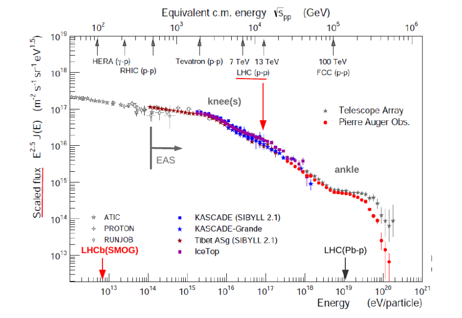


Proposal

search in HI collisions behind a neutron absorber shield

Muon deficit in cosmic rays just above LHC energies

Cosmic ray energy spectrum



Described by

- string fragmentation
- high density effects in hadronization
- diffraction
- higher order effects (multi-Pomerons)
- remnants

Muon production

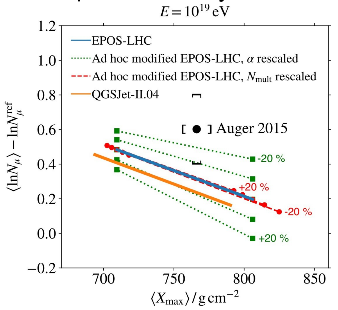
in air showers badly described

Muon deficit

in simulations

Ad hoc change of

muon production by $\sim +4\,\%$



uncertainties mostly due to

nuclear collision extrapolations

Need input

from light ion collisions data

Precision measurements in

pA and AA with $A < 20$ needed

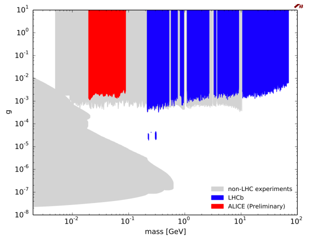
Ideal test

pO and OO collisions

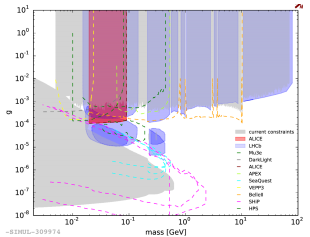
Although LHC results suggest that the muon deficit problem is due to SM uncertainties there is room for NP models

New Physics @ ALICE

Dark photon search Run 1

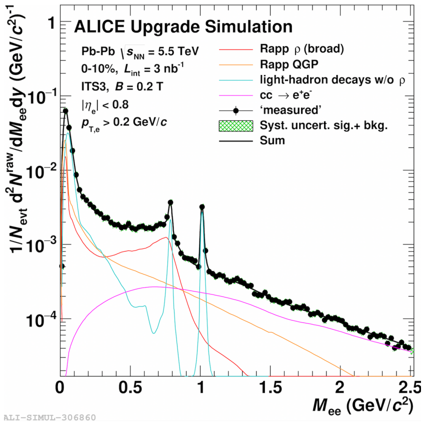


Projection Run 3 and 4

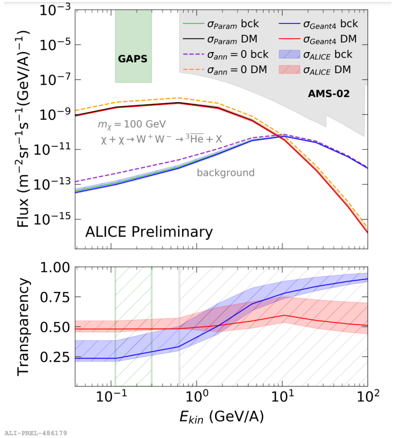


GeV scale dark boson under study

QGP is additional thermal source



anti-^{3}He cosmic ray predictions



Conclusion

- Second successful workshop on New Physics searches in heavy ion collisions
- Potential New Physics (more than presented in this talk)
  - Magnetic monopoles
  - Axion-like particles
  - Sexaquarks
  - Dark photons
  - Soft New Physics
  - Long-lived New Physics
- Connection to
  - Cosmic ray air showers
  - τ-lepton $g-2$
  - Gravitational waves
- Summary will be published as contribution to Snowmass 2021

Appendix

Upcoming HI runs at the LHC

PbPb and *p*Pb in Run 3 and 4

more collisions at LHCb
minor penalty for the others

1-month PbPb

2.2–2.8 nb^{-1}	ATLAS/ALICE/CMS
$\sim 0.5\,\mathrm{nb}^{-1}$	LHCb

~ 5 runs to reach targets

13 nb^{-1}	IP1/2/5
2 nb^{-1}	IP8

Future work

performance enhancements studies

1-month *p*Pb

530–690 nb^{-1}	ATLAS/CMS
310 nb^{-1}	ALICE
150 nb^{-1}	LHCb

Two runs sufficient

1200 nb^{-1}	IP1/5
600 nb^{-1}	IP2
factor ~ 2 missing	LHCb

Beam loss mitigation

Orbit bumps
Crystal collimators
(Dispersion suppressor collimators)

Options for short light ion run

with OO and *p*O

Motivation

physics interest
machine performance study for future light-ion operation

Run 5

Updated scenarios for light-ion operation under study

The SuperChic Monte Carlo event generator

Ultraperipheral HI collisions

$\gamma\gamma$ collisions key mode for BSM production

SuperChic 4 MC

full differential generator

Central exclusive processes (CEP)

- QCD induced
- photon induced

including survival factor for pp, pA, and AA

Examples

- τ-lepton $g-2$
- ALPs and light-by-light scat.
- Monopoles

Basic idea

$$\sigma = \int dx_1 dx_2 n_1 n_2 \hat{\sigma}_{\gamma\gamma\to X}$$

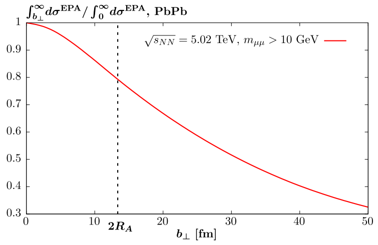
Photon flux n_i well known

in terms of EM form factor

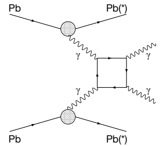
Survival factor captures

additional soft production

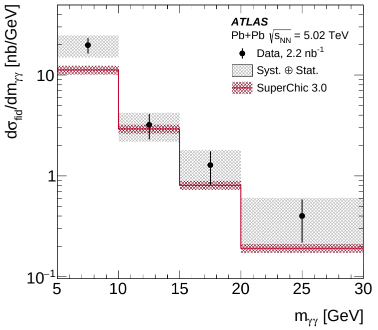
impact parameter dependence



ALPs @ ATLAS



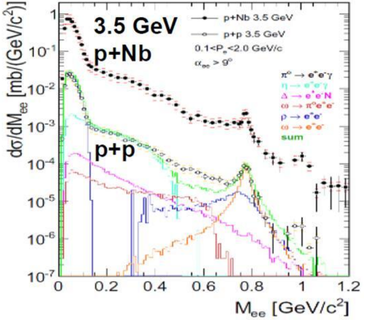
Good agreement with data



Light dark photons from meson decays

HADES

GSI SIS18 detector in Darmstadt



pp at 3.5 GeV

*p*Nb at 3.5 GeV

Ar KCl at 1.76A GeV

Theoretical description

with Parton Hadron String Dynamics (PHSD)

a non-equilibrium microscopic transport approach

Production of dark photons

in Dalitz decays

- $\pi^0, \eta \to \gamma\gamma_{dark}$
- $\Delta \to N\gamma_{\mathrm{dark}}$

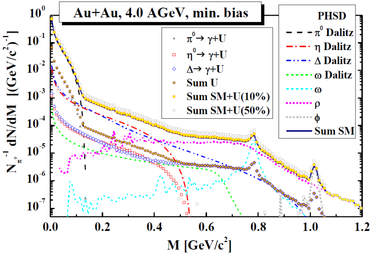
Decay into lepton pair

$\gamma_{dark} \to e^+e^-$

Described approach

allows flexible reinterpretation of experimental constraints

Predictions w/o exp. acceptance



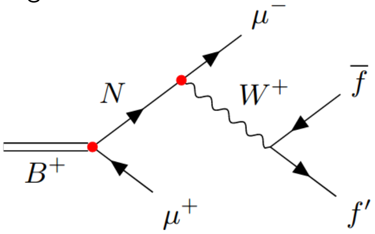
Reproduce

upper limit on kinetic mixing for $0.15\,\mathrm{GeV} < m_{\gamma_{\mathrm{dark}}} < 0.4\,\mathrm{GeV}$

Soft New Physics

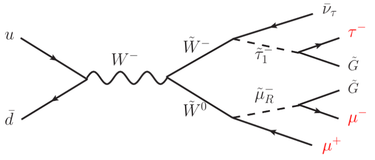
GeV-scale New Physics

Right-handed neutrinos

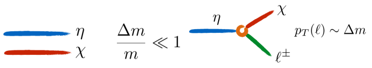


cascade decay

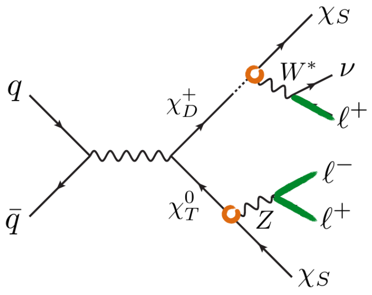
supersymmetry



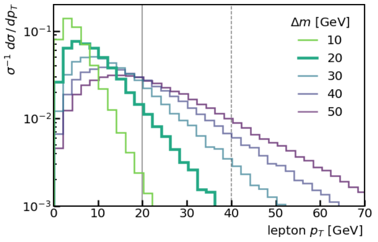
compressed dark sectors



Concrete DM model signature



Not detectable in *pp*



Idea: Soft leptons in HI

Higher Sensitivity due to lower trigger

Soft long-lived particles

Light right-handed neutrinos

long-lived
escape QGP unhindered

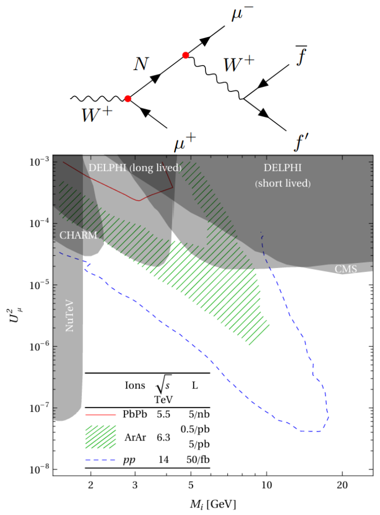
Ideas for searches

- exploit low triggers
- use lighter ions

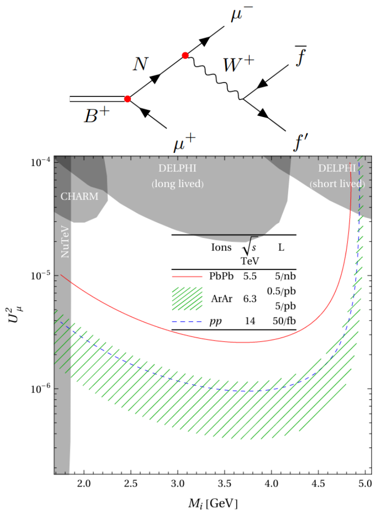
Lighter ions can have advantage

over *pp* collisions at equal running time

$W^\pm \to \mu^\pm N$



$B^\pm \to \mu^\pm N$



New particle observations in PbPb @ CMS

$X(3872)$ resonance

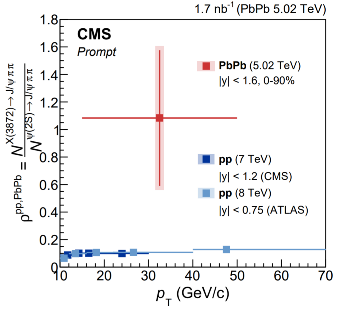
exotic meson with 1^{++}

Possible explanations

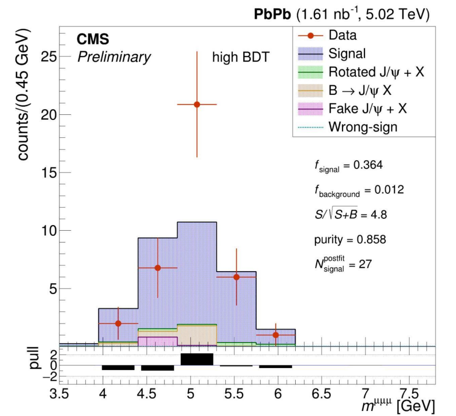
cucu Tetraquark

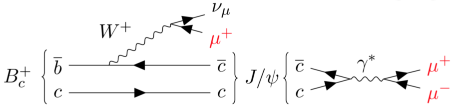
D^0–$\overline{D}^{*0}$ molecule

$X(3872)$ to $\psi(2S)$ yield ratio

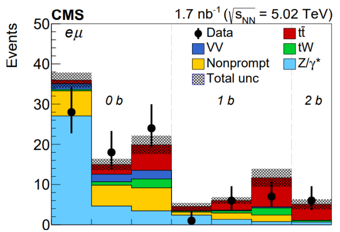


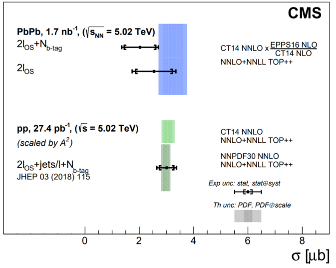
B_c in PbPb well above 5σ





$t\bar{t}$ production





Potential heavy New Physics in cosmic rays

Air showers

QCD interactions under extrem conditions

Interaction energy

considerably above LHC energy

Muon deficit problem

Air shower simulation produce much fewer muons for showers above 10^7 GeV

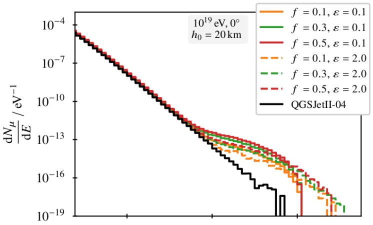
Idea: Heavy New Physics

that produces many muons

CORSIKA8

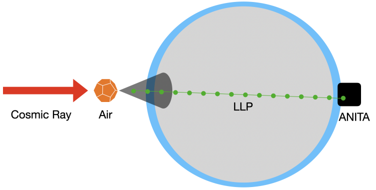
Framework for investigations of particle cascades in astroparticle physics

Simulation of New Physics models



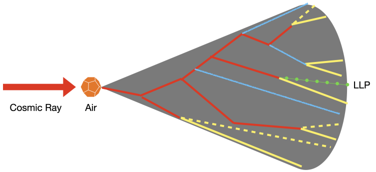
is able to explain the muon deficit problem

Can be linked to



ANITA excess

Connected to



long-lived particle searches in cosmic ray air showers

CASTOR Calorimeter @ CMS

Very forward calorimeter

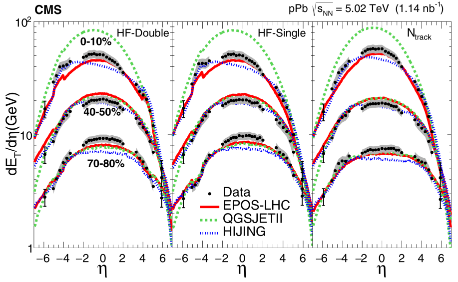
Successful data taking
in Run 1 and 2

Unique calorimeter data

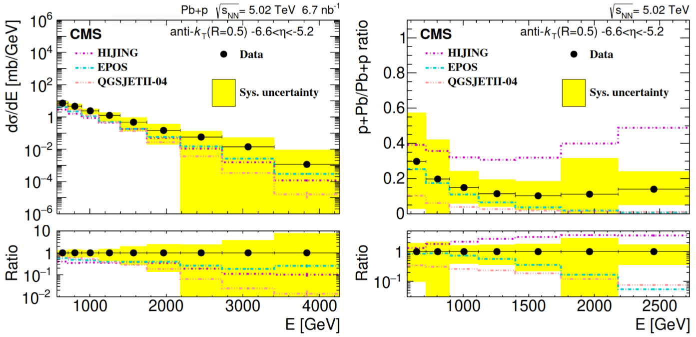
$-6.6 < \eta < -5.2$

Centrality and pseudorapidity dependence

of transverse energy density in *p*Pb



Inclusive very forward jet cross sections in *p*Pb



Potential studies of New Physics

Baryon-rich forward fragmentation region
search for strangelets and penetrating particles

Gravitational Waves

Proposal to test

mHz gravitational waves at LHC

Method

Change in bunch travel time due to change in test mass velocity

Velocity change causes

significant effect on travel time

LHC

used as storage ring

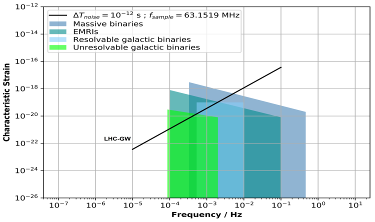
Needs additional

detection system

Noise sources

- Quantum noise (quantum uncertainty in time-tagging proton bunches)
- Gravity gradient noise (due to sun, moon, alps, ...)
- Seismic noise
- Radio frequency phase noise

Sensitivity



Idea

Probe gravitational waves during heavy ion runs

Questions

Effect of rest gas collisions

Effect of synchrotron radiation

Impact of lower energy